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CURRENT PERFORMANCE OF THE NASA BIOMASS PRODUCTION CHAMBER

by

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SUMMARY:

NASA's Biomass Production Chamber (BPC) is the main component of the Controlled Ecological Life Support System (CELSS). It is a 7.5m by 3.7m cylindrical chamber in which plants are grown hydroponically. The chamber is sealed and nutrient solution and atmosphere are recycled. Several tests have been performed to measure the performance of the chamber. Results of these tests, along with a description of the general operating characteristics, are presented.

KEYWORDS:

Controlled environment, CELSS, growth chambers, recycling, space program.

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Introduction

Human exposure to space has been limited to short duration missions with all necessary supplies taken or received from Earth. In order to make long duration missions feasible, all consumables necessary for life support will have to be recycled as much as possible. With that idea, NASA began research in 1978 into controlled ecological life support systems (CELSS). The main goal was to combine biological and physicochemical systems to produce food, breathing air and potable water by recycling waste in a stable, reliable manner (Averner, 1989).

In 1985, NASA personnel at Kennedy Space Center proposed the development of a CELSS Breadboard to test and demonstrate bioregenerative components. That same year work began on a bioregenerative life support system, the CELSS Breadboard Project, to provide a test bed for large scale demonstration of current CELSS research. Since green plants are central to CO_2 removal and O_2 production, potable water generation and food production, the first component in the CELSS Breadboard Project was the Biomass Production Chamber (BPC). In this way, the current state of controlled environment plant production could be duplicated and studied. Various options for growing plants could be tried, helping to identify the "best set" for a given senario. Also, by growing plants in closed environments, the atmospheric contaminants produced could be determined (Prince and Knott, 1989).

The BPC was originally used for low pressure testing on Mercury space capsules. It is 7.5m high and 3.7m in diameter. Originally, the chamber was physically (but not atmospherically) separated by the addition of a floor. Recently, though, the floor seams were welded shut to create two separate chambers. Efforts are still ongoing to completely quantify the separation of the two part chamber. This leaves an upper and a lower level, each with two shelves for growing plants. With the addition of fans and air ducts for the upper and lower levels, total chamber volume is approximately $113m^3$, with approximately one half of the total volume for each level. Figure 1 shows the outside of the chamber. Plants grow hydroponically in trapezoidal-shaped trays shaped to fit the annular configuration. There are 16 trays per shelf with each shelf having its own supply of nutrients. Total hydroponic growing area of the trays is $16m^2$, and if the area between the trays is included the area under the crop canopy is $20m^2$. Above each growing shelf are two lamp banks made up of eight lamp canopies. Each lamp canopy contains three 400W high intensity discharge (HID) lamps. These lamp canopies have high pressure sodium (HPS) lamps and ballasts, but metal halide (MH) lamps designed to operate on HPS ballasts have also been used. Individual banks of lights can be dimmed to provide varying amounts of photosynthetically active radiation (PAR) ranging from 200 to $700\mu moles/m^2/s$ PPF. Each lamp has an adjustable stainless-steel parabolic reflector to provide uniform irradiance of the crop.

Control of aerial parameters; CO_2 concentration, temperature, humidity, photoperiod; and nutrient parameters; electrical conductivity, pH, temperature, and liquid level; is provided by a programmable logic controller (PLC). The monitoring of these parameters has been separated using different sensors. These data were originally collected and stored by a data-logger, but are now collected on an engineering workstation and stored on a minicomputer.

For a detailed chronological history of the chamber, including plant experiments, see Wheeler, et al., 1990.

The principal component parts of the BPC will be described in detail in the following section. They include the air handling units, condensate recovery system, nutrient delivery system, lighting system, monitoring and control, and atmospheric control system.

<u>Air Handling Units (AHUs)</u> - The AHUs have remained basically the same since the initial installation. Air is blown horizontally across the growing shelves and the plants. It is returned through a standard air filter to remove any airborne plant particles, such as leaves, and across the lamps to help remove heat. The air then passes through the blower. From the blower the air passes through cold and hot water coils, through a filter bed and back to the chamber. There are two 30kW blowers, one for each level, to provide air circulation. A high efficiency particulate air (HEPA) filter is installed in the upper and lower ducts to help clean the air as it circulates. The filters are 99.97% efficient at removing particals 0.3 micrometers in diameter. There is a prefilter and a coarse air filter upstream from the HEPA filter. Cooling and dehumidification is provided by two 52kW chillers. The 96 400W HPS lamps provide the majority of the heat in the chamber during the day. However, a 150kW water heater provides heating for more accurate temperature control. Originally, supplemental humidification was intended to be provided by two steam humidifiers. However, these were removed due to operational problems and spray nozzles using deionized water were installed. Two spray nozzles were installed immediately following the HEPA filter in both the upper and lower AHUs. Providing an atmospherically-closed system has been a continuing problem. The blower drive shafts were identified as a large air leakage point and deionized water droplets were used at one time to help atmospherically seal around them, but that has been discontinued. All duct work was coated with a silicon-based sealant and covered with neoprene insulation. This has helped to reduce the atmospheric leakage to under 10% of the total chamber volume per day. This figure will change depending on the work done on the chamber. Opening sealed access ports or modifications to

the plumbing all increase the leak rate. The most recent change has been the addition of a pressure control system. This consists of a 576L compressed air tank and a 7.5kW compressor to either add or remove chamber air as the chamber pressure moves outside of a preset range. Use of this system has helped remove pressure transients greater than 50pa caused by the change from one temperature set point to another. Small pressure fluctutations caused by the flow of hot and chilled water in the heating and cooling coils is not affected.

Condensate Recovery System - In order to track water usage and to eventually recycle water used, condensation from the cooling coils is collected. Originally, 115L stainless steel collection tanks beneath each air duct were used. The water level was recorded manually and makeup water was added from the facility deionized water supply. To hold the condensate for use, two storage tanks of 300L each were added and the condensate was automatically pumped from the collection tanks to the storage tanks. The stainless steel tanks were replaced by smaller PVC tanks of 2L each, giving the system better volumetric sensitivity and its current configuration. Pumps to move the condensate to the storage tanks are actuated by liquid level switches after a constant volume of 1.5L is collected. Once the condensate is pumped to the storage tanks, it is automatically circulated through deionizing and filtering columns to remove any particulate matter. There are two deionizing columns (one is a backup) and a 0.2 micron filter column for each condensate storage tank. From the condensate storage tanks, water can be either pumped to the nutrient tanks as makeup water, or be drained from the system.

Nutrient Delivery System (NDS) - The nutrient delivery system has undergone the most change of any of the original systems. Originally, nutrients were kept in tanks inside the BPC. Nutrient and pH balance were manually controlled. As construction inside and outside the BPC was completed, the tanks were moved outside and plumbed into a complete system. Each growing level has its own tank of nutrients and is isolated from the other levels. The nutrients are circulated by a 0.5kW pump with an identical backup pump. Flow is controlled by manual ball valves located throughout the plumbing. The most recent change has been the method of controlling nutrient temperature. Originally, water from a 15kW chiller was circulated through a jacket surrounding each NDS tank. However, the tank material would not allow sufficient heat transfer to control the temperature. Nutrient temperature is now controlled by circulating chilled water through a stainless steel coil in each tank.

Nutrient liquid level, electrical conductivity (EC) and pH are automatically controlled. Each level is controlled independently of the other three levels. Makeup water for a nutrient tank comes from the condensate recovery system (see above) or the deionized water supply. When nutrient solution level in the tank drops below a setpoint, condensate water from the air handling units is pumped into the nutrient tank. When the nutrient EC measurement moves outside of a preset range (120-130mS/m), a set amount of a stock solution of nutrients is automatically added by a metering pump. Solution pH is controlled in much the same manner, with a dilute solution of nitric acid added to lower the pH. Each level has a separate supply of stock solution and acid so independent nutrient regimes could be run on each of the four growing levels.

Lighting - Lighting inside the chamber is provided by 96 400kW HPS lamps. There are three lamps for each canopy. Dimming ballasts were installed to control light levels in different sections of the BPC. Control is divided between the upper left, upper right, lower left and lower right sections for each half of the chamber for a total of eight banks of light control. There have been no changes made to the original lighting system since installation, except for occasional use of metal halide lamps designed for use with HPS ballasts.

Monitoring and Control System - From the beginning, system control has been provided by a programmable logic controller (PLC). This is an industrial controller which combines ladder computer logic with the ability to handle substantial levels of electrical power. It controls temperature and humidity, light levels, nutrient and pH levels, and any other component that affects the plant environment. In addition, it provides a degree of safety against catastrophic occurrences by having the ability to make simple decisions based on certain combinations of events and trigger a central alarm.

The current monitoring system is based on an engineering workstation using standard analog/digital input/output hardware and custom written software. This replaced the datalogger originally used to monitor and store system measurements. The monitoring system uses completely separate sensors to provide a check of control sensor accuracy. It also has the ability to graphically display data. Both monitoring and control data from past experiments is stored on a shared minicomputer where it is available for data analysis.

Atmospheric Control System - A four gas control system was originally installed using CO_2, O_2, N_2, and breathing air (N_2 and O_2) supplies. Gases inside the BPC are measured and controlled using gas analyzers in a closed circuit which returns the sample to the BPC. The only gas currently controlled is CO_2. Oxygen is measured but not controlled. Carbon dioxide was controlled by adding breathing air to the chamber whenever CO_2 levels went above a certain level, and adding CO_2 from gas bottles whenever it dropped below a certain level. However, this was abandoned after it was determined that large amounts of breathing air would be required to dilute the CO_2 given off by the plants during the dark cycle. After the chamber became adequately sealed to track CO_2 buildup, it was decided to only add CO_2 as the plants used it.

Original plans to custom mix the atmosphere inside the BPC were put aside due to safety concerns about using pure oxygen. Since then, ambient air has been used in the chamber. Oxygen buildup is slight, since normal work routines do not allow the chamber to be sealed for more than a few days at one time. Currently plans are to add an oxygen concentrator to remove excess oxygen from both chambers of the BPC. This will allow the chamber to be sealed for long durations during a plant experiment.

Carbon dioxide is measured using two infrared gas analyzers (IRGA), one for each level of the BPC. These are used for the control system. There is a third IRGA connected to the monitoring system which automatically samples the upper BPC, lower BPC, hangar air, and outside air. Oxygen is measured using the same two IRGAs (which contain a fuel cell) connected to the control system, and a separate oxygen sensor for the monitoring system. Again, the monitoring system measures the upper BPC, lower BPC, hangar air, and outside air. Automatic calibration is performed on both the control and monitoring analyzers daily, with a complete manual calibration being performed weekly.

Objectives

Tests were conducted to more objectively assess the performance of the BPC. The main goal was to first determine the operating range for critical environmental parameters. This will allow us to better plan future crop and system tests and to anticipate potential problems. During the "downtime" period between crop experiments, the BPC was operated to determine the following:

1) Minimum air temperature attainable
2) Maximum and minimum nutrient temperature attainable
3) Minimum relative humidity attainable
4) Power consumption of lamps for a given output
5) Effect of pressure control system on leakage

These tests were conducted using the standard instrumentation and sensors in the BPC and used during crop experiments. However, there were no crops in the chamber during any of the tests.

Results

Air Temperature - Minimum air temperature was attained by overriding automatic control of the valves which allow hot and chilled water through the coils in the air ducts. The chilled water valve was then forced completely open (100%) while the hot water valve was held closed (0%). Chilled water temperature averaged around 8°C, though this fluctuated as the compressors cycled on and off. There was no nutrient solution flowing during the test. Lights (a main source of heat) were turned off for one test, then turned on for a repeat test. Figure 2 shows the minimum air temperature with lights off to be 10°C. Air temperature reached close to the chilled water set point and remained fairly constant. Results from the test repeated with the lights on are shown in Figure 3. The minimum air temperature attainable rose to 15°C and showed a tendancy to rise further the longer the test ran. Temperature fluctuations were also more pronounced due to the heating inside the BPC from the lighting. Minimum air temperature is the chilled water temperature plus 2°C with lights off, and chilled water temperature plus 7°C with lights on.

A test for maximum air temperature was not run. Experience has shown that the air temperature can easily rise above 40°C in a short period of time. This temperature would not be desirable for plant growth, and would probably have a harmful effect on system hardware, including sensors and thermoplastic growth trays.

Nutrient Temperature - Maximum nutrient temperature was determined by disabling the nutrient cooling system and running the circulation pumps for the solution. There is no supplemental heating of the nutrient solution. The only heat supplied is from ambient conditions and by the pumps. Air temperature was set at 22°C. The test was initially run with the lights off. It was then repeated with the lights on. Figure 4 shows the temperature of the four nutrient levels rising as the pumps circulate the solution. Level 3 did not rise as high as the other 3 levels because the pump was short-cycling, caused by a faulty sensor. Although this was not planned, it shows the amount of heat added by the pumps (approximately 0.5kW each). Figure 4 also shows the effects of ambient temperature as you see the temperature rise and fall with the day/night cycle. Figure 5 shows the slight amount of heat added (approximately 1°C) from the lights inside the BPC.

Minimum nutrient temperature was determined by setting the control point for the same temperature as the nutrient chiller set point, 5°C. Tests were run twice, once with the lights off and again with the lights on. The results are shown in Figures 6 (lights off) and 7 (lights on). Nutrient chillers were enabled following the maximum nutrient temperature test. This shows the worst-case response time of approximately five hours to traverse the entire temperature range of 27° to 12°C. Turning on the lights raised the nutrient temperature 1°C.

Minimum Relative Humidity - Minimum relative humidity was determined by opening the chilled water coil to 100% and letting the hot water coil try to maintain temperature. Figure 8 shows the results of this test. Chilled water temperature averaged 12°C. Air temperature was set at 22°C, although it never rose to that point after opening the chilled water coil. From the psychrometric chart, the minimum relative humidity attainable should have been around 55-60%, and we reached 65%. During automatic control of humidity, the operating range falls between 70 and 80%. The failure to reach the maximum operating limits is due to the inability to remove condensed water from the coil before it is blown back into the air duct.

Lamp Power Consumption - Two dimming ballasts were tested. Current drawn was measured for a given amount of light output. Figures 9 and 10 show similar shapes, although the absolute numbers are not the same. The curves are typical of the silicon-controlled rectifiers (SCR) used for dimming the bank of lamps. As the lamps are dimmed, the amount of current drawn by the ballast is decreased, until the SCR begins to create a reactive load, then the current increases. This is a typical characteristic of SCRs.

Pressure Control System - The BPC is tested for leakage during non-crop experiments by raising the carbon dioxide level and measuring the decay rate. The leak rate is calculated using the formula described by Sager, et al (1988). Two tests were conducted, one with the pressure control system enabled and the other with the pressure control system disabled. The results in Figures 11 and 12 show that leakage is slightly reduced from over 11% to approximately 10% of the total chamber volume per day.

Summary and Conclusions

The Biomass Production Chamber (BPC) is the major component in the CELSS Breadboard Project. Baseline data was needed to understand the capabilities of the chamber for crop growth experiments. It was also needed in order to measure the effects of current and future modifications. Tests were conducted on the main components of the BPC. Minimum air temperature, minimum and maximum nutrient temperature, minimum relative humidity, chamber leakage, and lighting power consumption were all measured. The chamber behaved as expected, however there remains room for improvement.

Temperature stratification and poor humidity control are both symptoms of the same problem: inadequate monitoring and control of the heating and cooling coils. Using flowmeters to measure hot and chilled water flow through the coils and tying that to the actuator and bypass valves should allow better control. Instrumentation to do this has been ordered. Different control algorithms will also be developed along with increasing the difference between hot and chilled water temperatures.

Control of nutrient temperature improved dramatically with the addition of the stainless steel coils to the nutrient tanks. However, the nutrient solution will have to be monitored closely to see that no materials toxic to the plants leach from the coils and accumulate in the nutrient tanks. In a closed system where all materials are recycled, this could have serious consequences in long-term operation.

In building the BPC and its components, energy efficiency has not been a priority. However, energy consumption will have to be quantified in order to understand the system operation and be able to compare it to competing systems. One of the largest energy consumers is the lighting, therefore the power consumption of the lights was measured. There were no surprises in the response seen, with the curves being typical of the dimming devices used.

Reducing chamber leakage is a primary concern. Adding a system to control pressure fluctuations was intended to help control leakage by reducing major pressure spikes during temperature changes. The results show how the pressure control system slightly reduced the leak rate. However, when a volume of air equivalent to the compressed air tank volume leaks from the system (2-3 days), the system can no longer operate since it has no air to add to the BPC to raise pressure. To help this situation, a bank of breathing air bottles were added to the gas control system. When the pressure in the compressed air tank drops below a certain point, breathing air is added to the BPC instead of air from the compressed air tank. The long term solution to this problem is to continue to double check all fittings, ports, plumbing and any other attachments to the main chamber and make sure they are sealed.

Future operations planned for the BPC include the complete closure of the liquid loop by using condensate water for humidification. This will complete the recycling of gases and liquids in biomass production. After that, resource recovery components will be included with the BPC to close the material loop. This will allow the recycling of gases, liquids and solids. Beyond this, efforts will be focused on food processing, robotics, material handling and automation. Opportunities exist for engineering research in these areas and these technologies will serve a major role in the production of a Lunar or Martian base.

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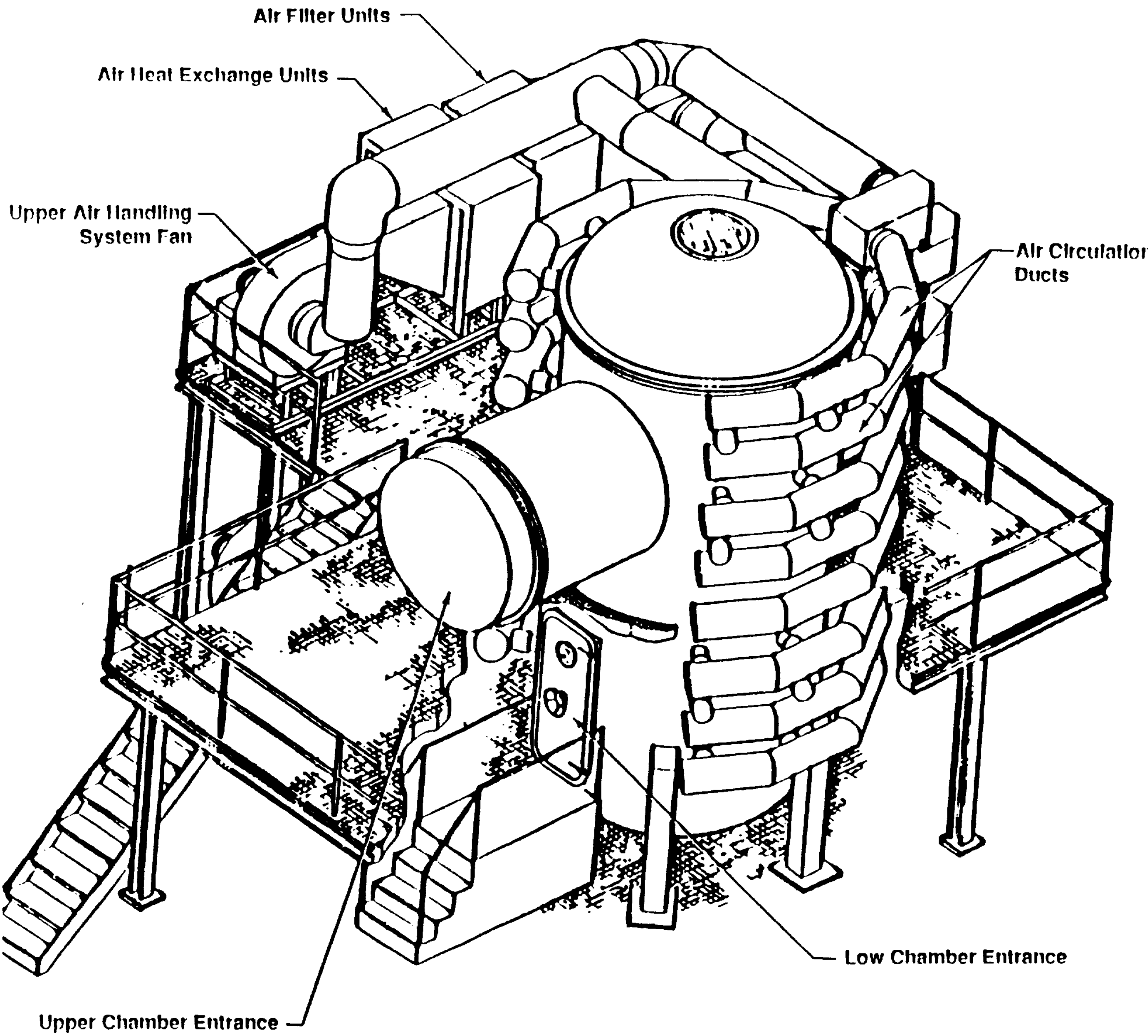

Fig. 1 NASA's Biomass Production Chamber (BPC)

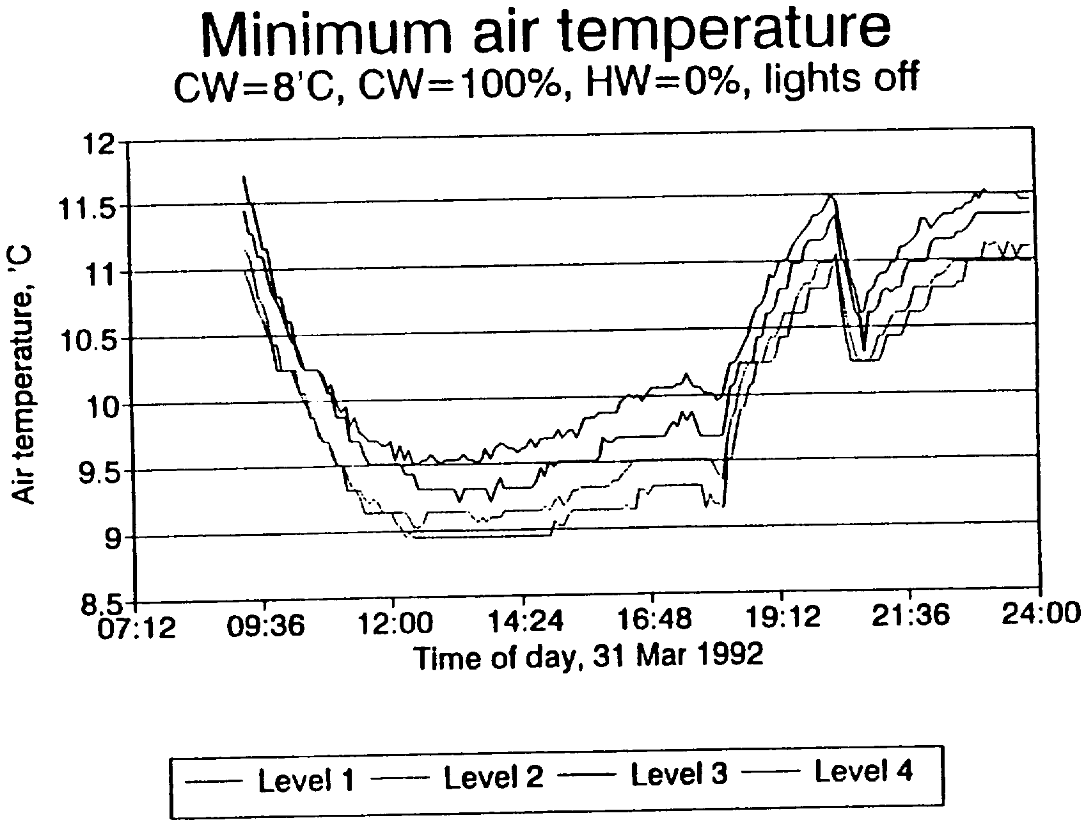

Fig. 2 Minimum air temperature, lights off

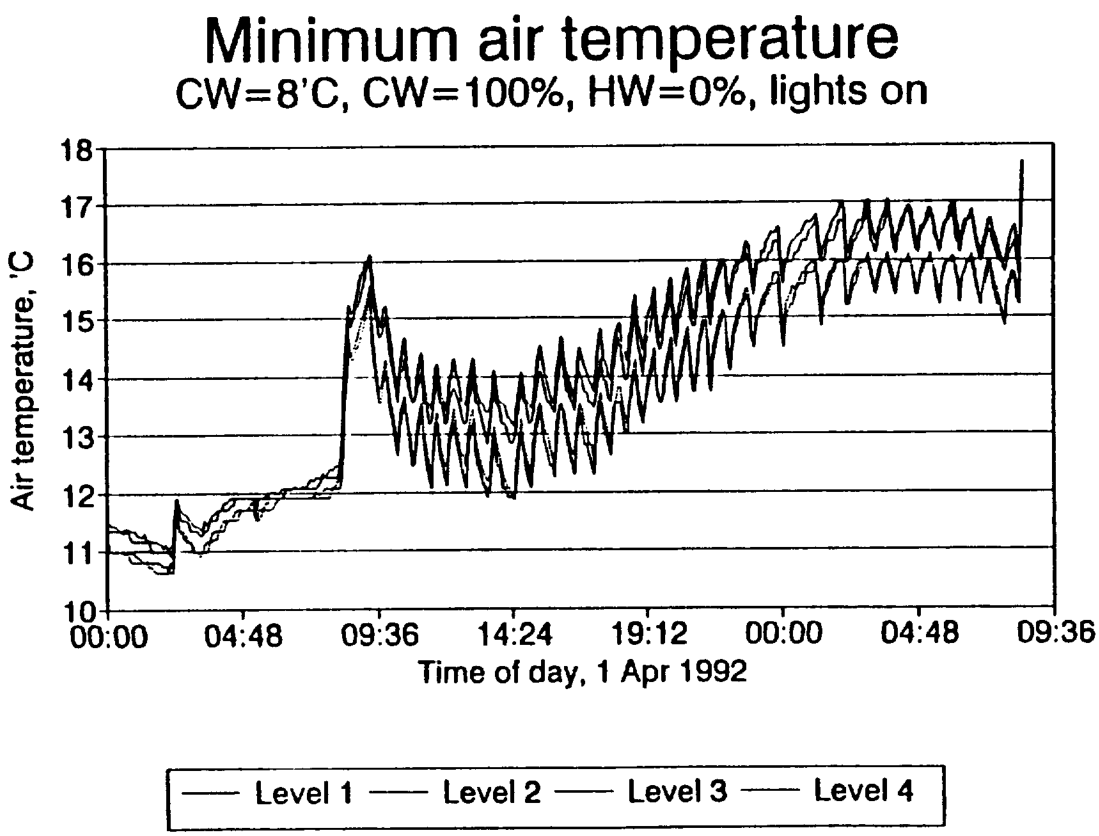

Fig. 3 Minimum air temperature, lights on

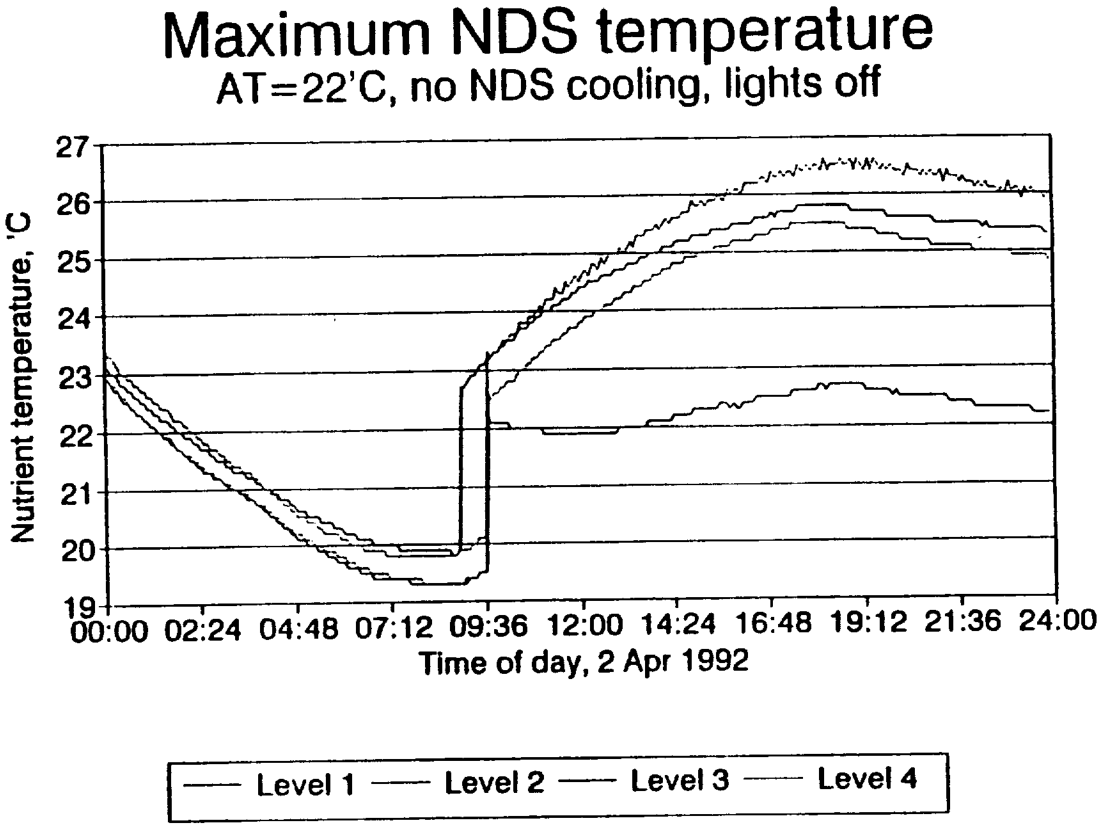

Fig. 4 Maximum nutrient temperature, lights off

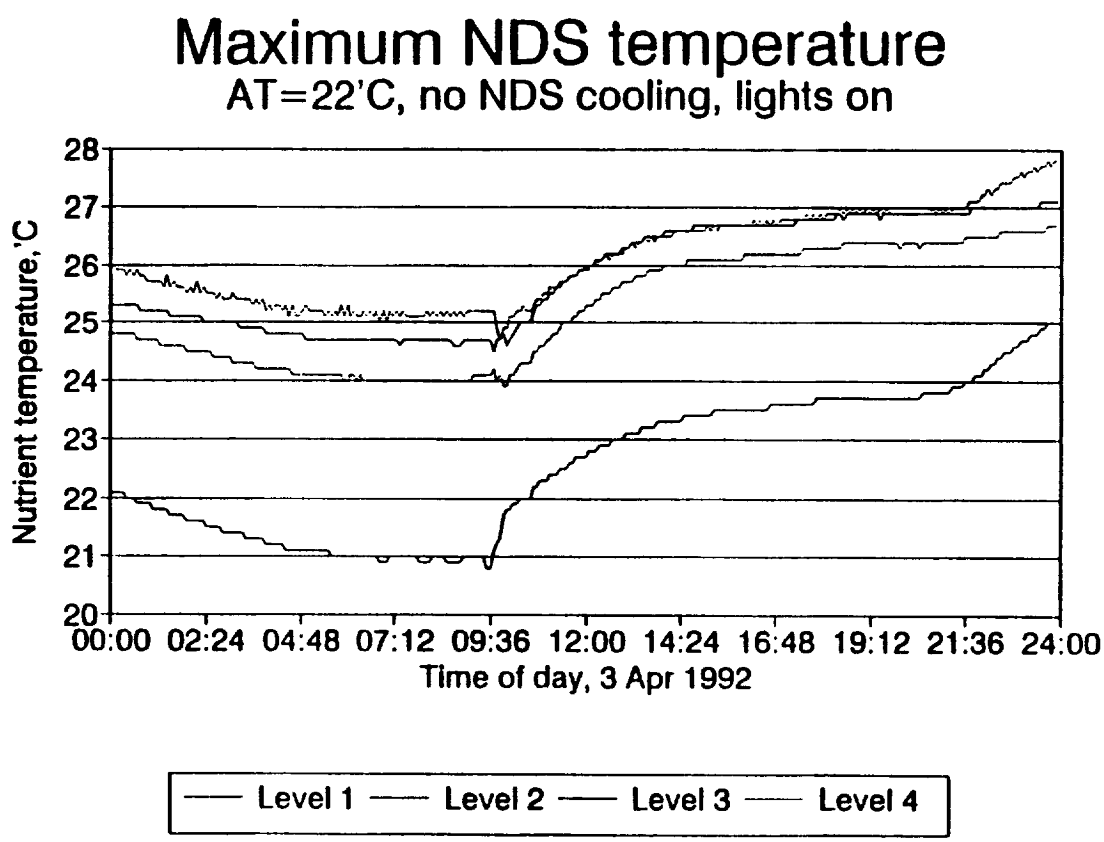

Fig. 5 Maximum nutrient temperature, lights on

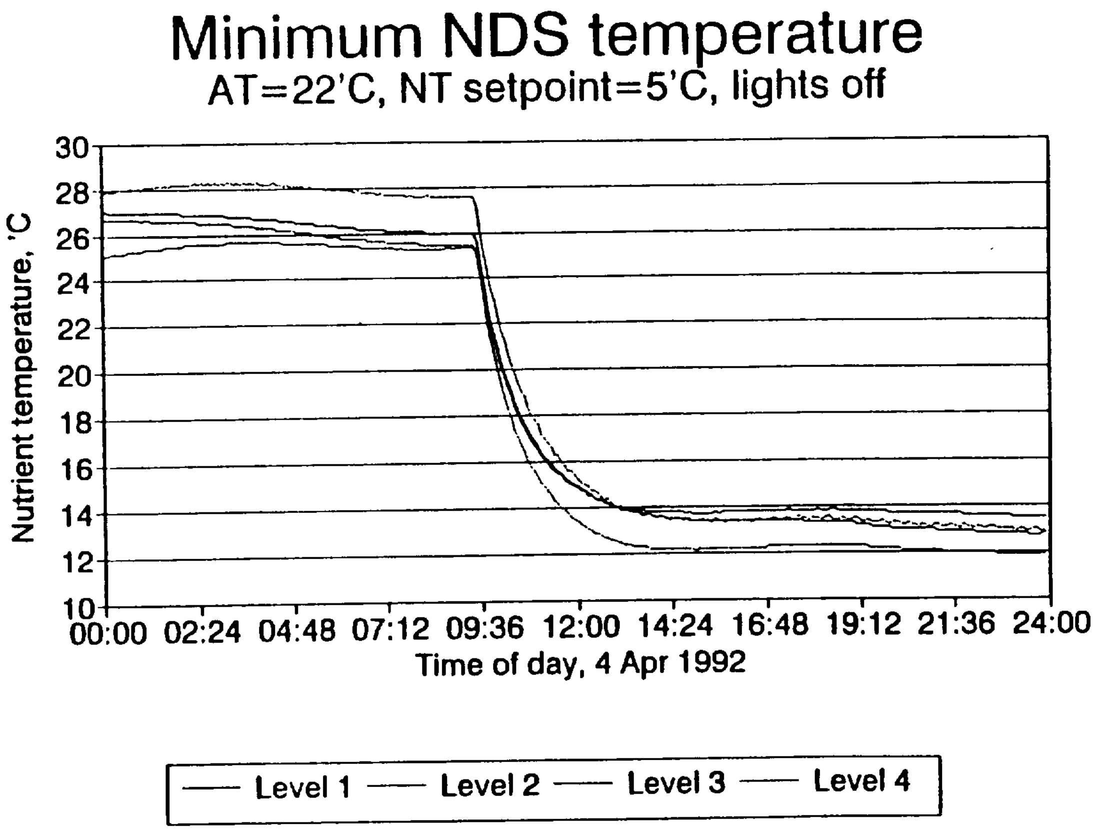

Fig. 6 Minimum nutrient temperature, lights off

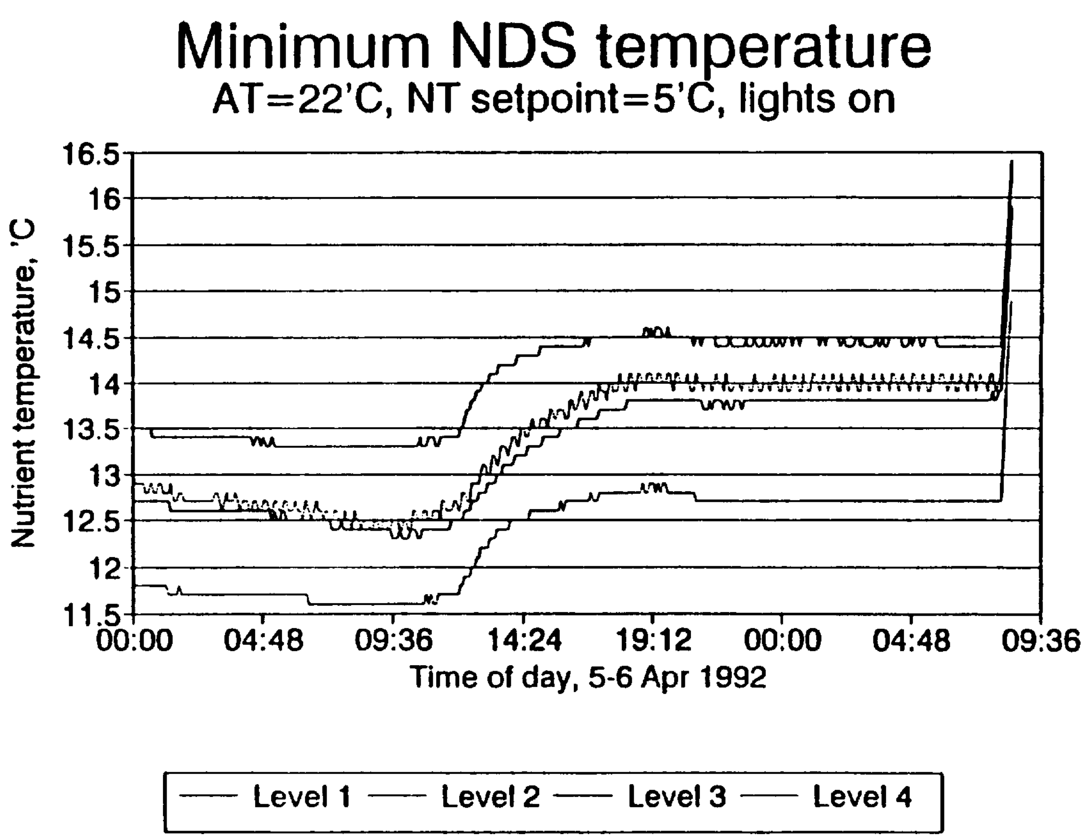

Fig. 7 Minimum nutrient temperature, lights on

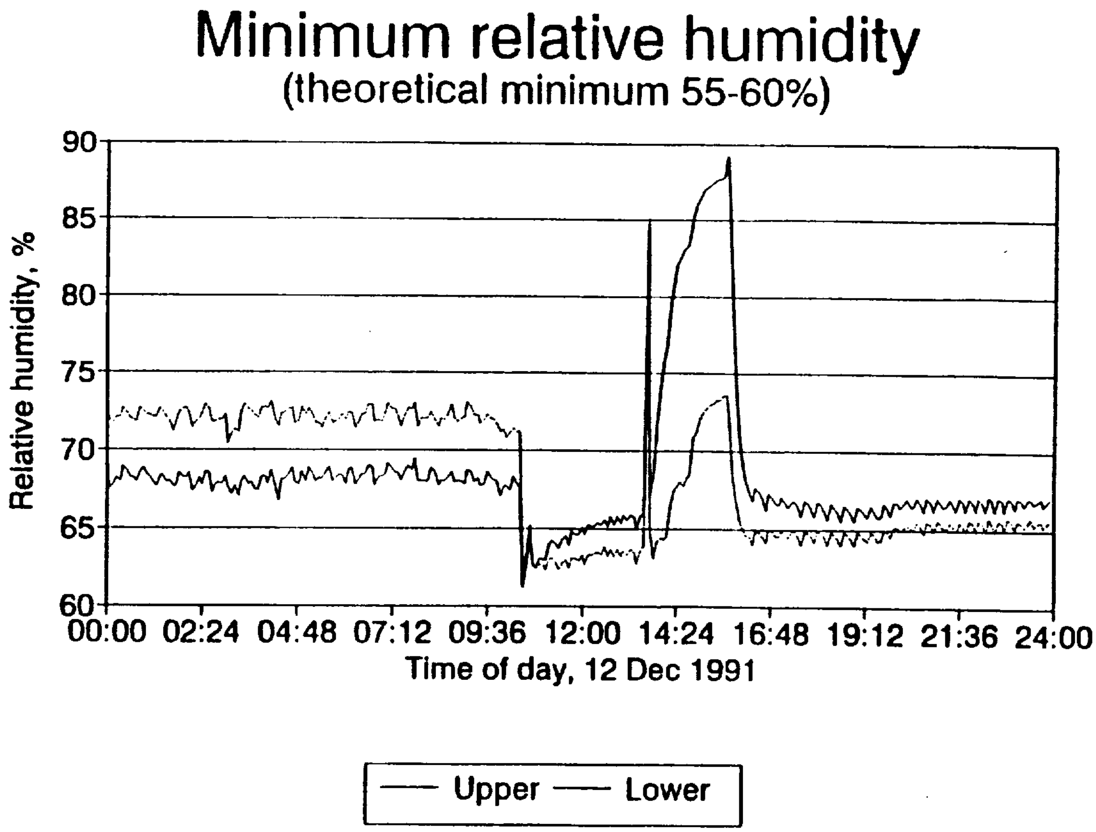

Fig. 8 Minimum relative humidity

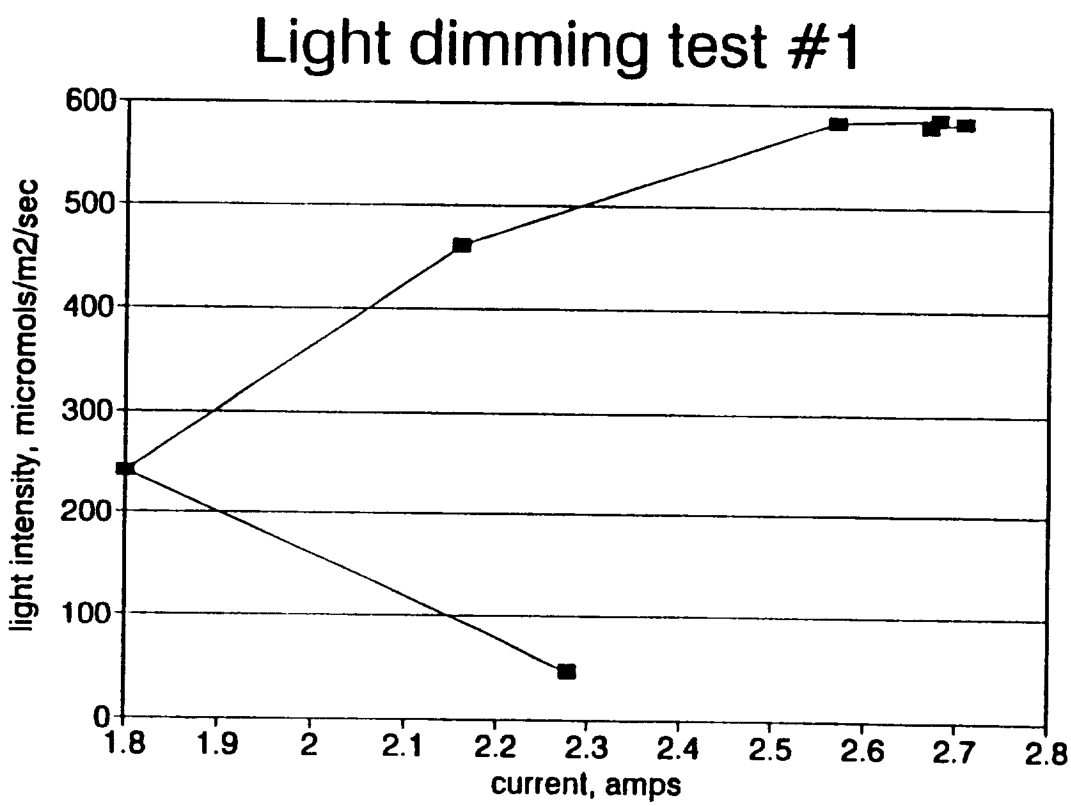

Fig. 9 Current drawn for different lighting intensities

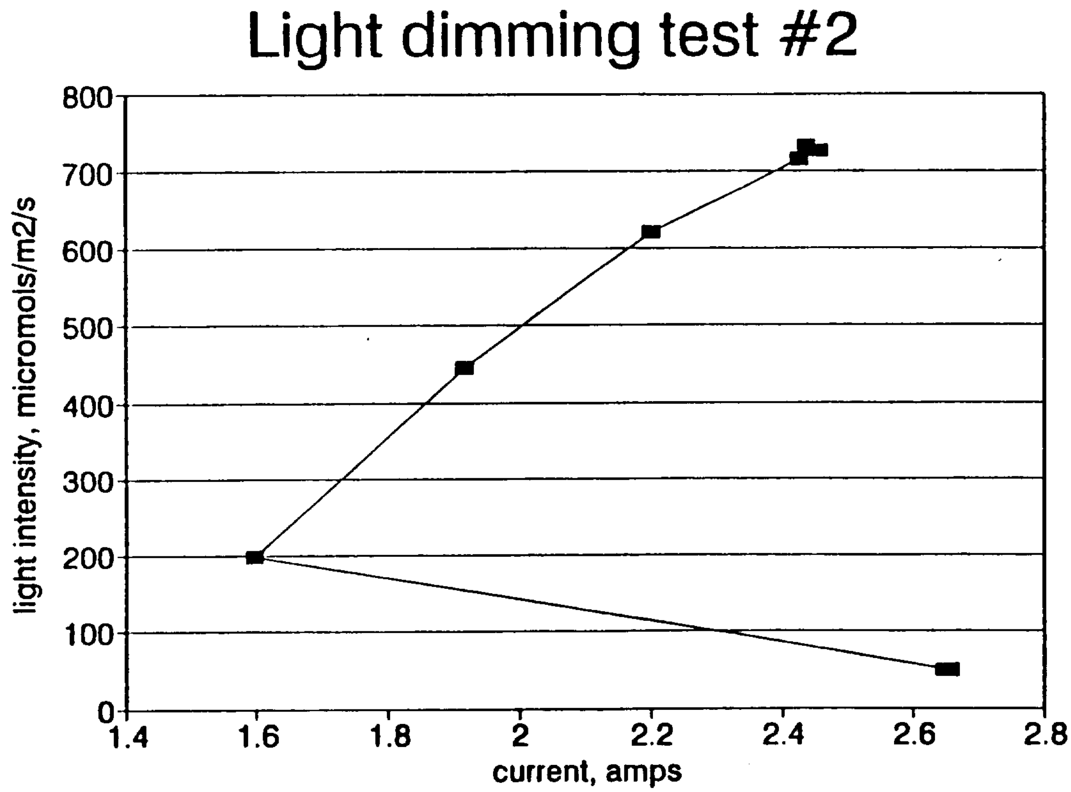

Fig. 10 Current drawn for different lighting intensities

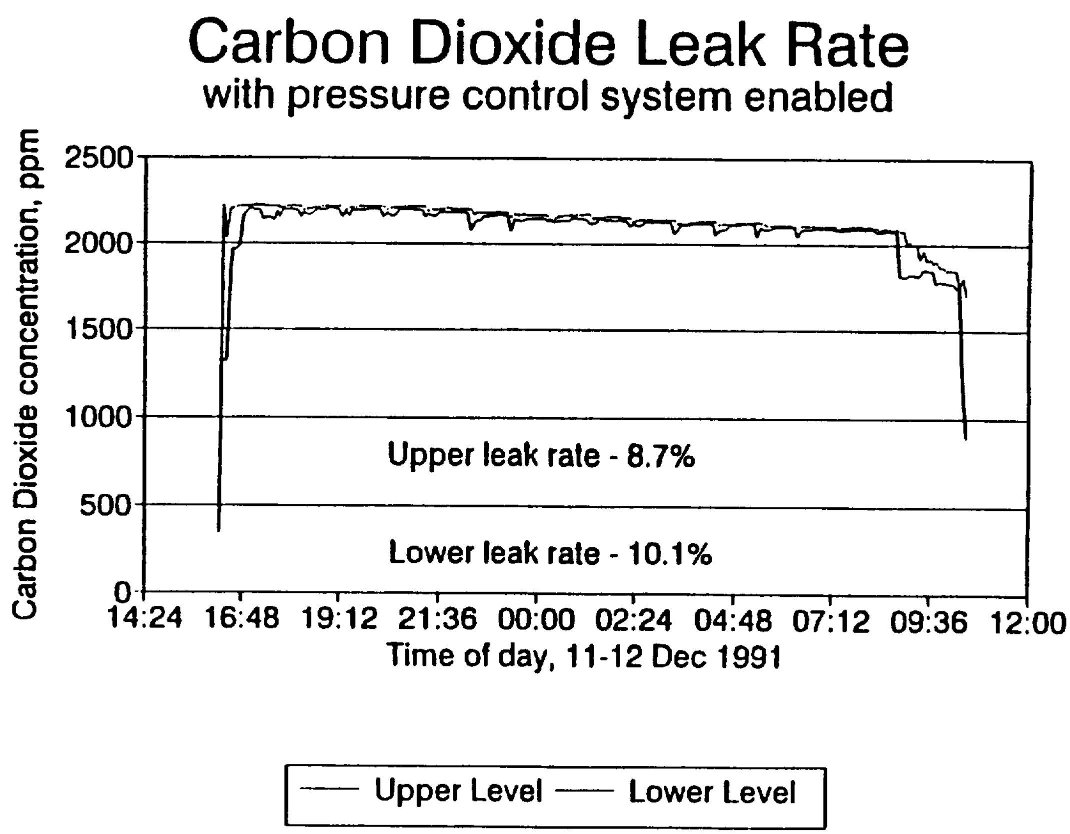

Fig. 11 Chamber leakage with pressure control enabled

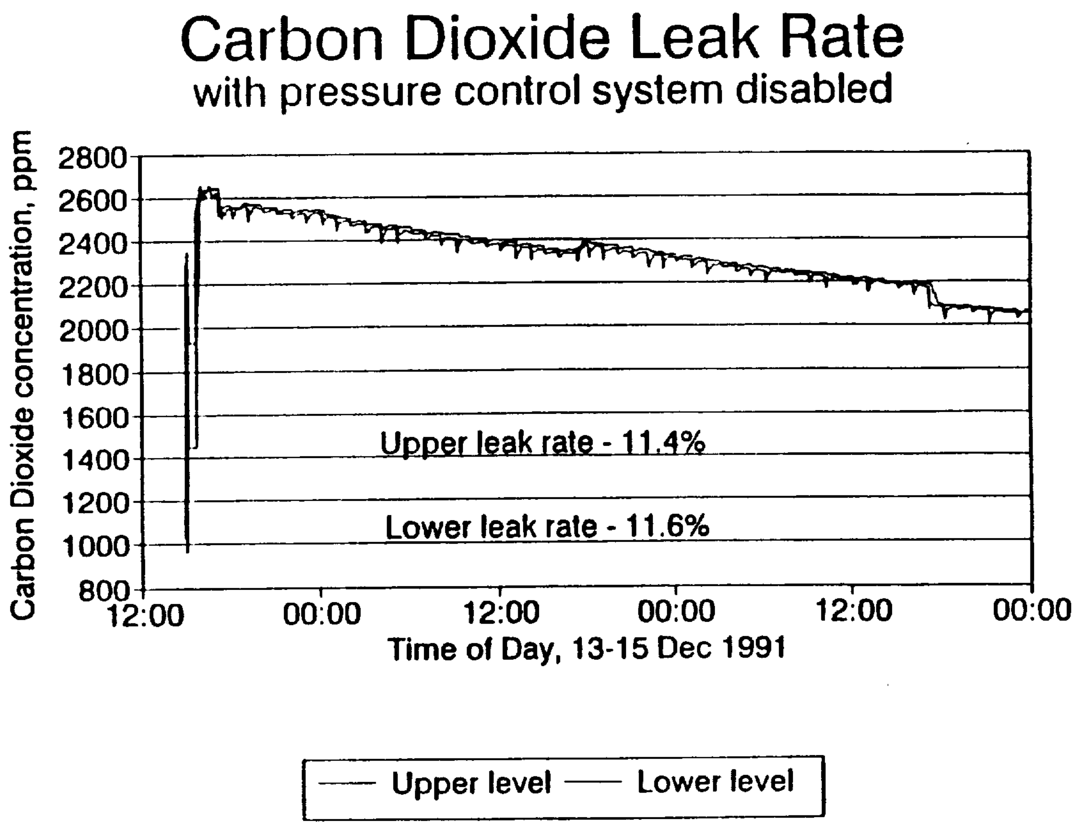

Fig. 12 Chamber leakage with pressure control disabled